

Nitrogen Fertilizer Use Efficiency of Furrow-Irrigated Onion and Corn

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ABSTRACT

Furrow-irrigated onion (*Allium cepa* L.) production, with high N fertilization rates, may be contributing $\text{NO}_3\text{-N}$ to ground water in southeastern Colorado. This study determined the growth and N uptake patterns of onion grown on a silty clay soil, N fertilizer use efficiency (NFUE) of onion, and recovery of residual N fertilizer by corn (*Zea mays* L.) following onion in rotation. Onion was sampled biweekly from 18 May to 15 Sept. 1998 from plots receiving 0 and 224 kg N ha^{-1} . Nonlabeled N and labeled ^{15}N fertilizer were band-applied near the onion row in split applications of 112 kg N ha^{-1} each on 18 May and 25 June. Onion dry matter accumulation was slow from planting to about late May, followed by a rapid increase in biomass production and N uptake. Because residual soil $\text{NO}_3\text{-N}$ was high, N fertilization resulted in only a small increase in bulb yield. Greatest demand for N by onion occurred during bulb development. Fertilizer N recovery by onion was 11 and 19% for May and June N applications (average 15%), respectively. Much of the fertilizer N remained in the upper 60-cm soil profile at harvest and had moved toward the onion bed center. Fertilizer ^{15}N detected at 180-cm soil depth indicated leaching losses from the root zone. The unfertilized 1999 corn crop recovered 24% of fertilizer N applied to onion for a total fertilizer N uptake by the two crops of 39%. Delaying N fertilizer application until onion bulbing begins may improve NFUE. Planting corn directly on the previous onion bed may result in greater N fertilizer recovery by corn.

APPLICATION OF HIGH RATES OF N to the shallow-rooted onion crop is a common practice by western USA onion growers. In the Pacific Northwest, growers apply high rates of N to onion to maximize marketable yields and the percentage of large-sized onion bulbs (Brown, 1997; Brown, 2000; Drost et al., 1997; Painter, 1980; Stevens, 1997; Thornton et al., 1997). Sammis (1997) also reported the need for high rates of N on onion to optimize yield in New Mexico but expressed concern about leaching of $\text{NO}_3\text{-N}$ from the root zone and the low N fertilizer use efficiency (NFUE) (30%) of onion. Sullivan et al. (2001) and Brown (2000) developed nutrient management plans for onion production in the Pacific Northwest to help reduce N application rates, improve N use efficiency (NUE), and minimize the detrimental effects of fertilizer N on ground water. Schwartz and Bartolo (1995) developed similar nutrient management guidelines for Colorado. Although these N fertilizer management guidelines recommend limiting N application when soil N is high, growers often apply N to ensure high yields and quality. Nitrogen nutrition can influence

onion bulb development, flavor, and bulb quality (Brewster and Butler, 1989; Randle, 2000). Bartolo et al. (1997) and Brown (1997) point out that N fertilization costs are generally <2% of onion production costs; therefore, growers are not very concerned about N application rate, other than insuring that sufficient N is present.

The Arkansas River Valley in southeastern Colorado is a major production area for melon (*Citrullus lanatus* Thunb. and *Cucumis melo* L.), onion, and other vegetable crops produced in rotation with alfalfa (*Medicago sativa* L.), corn, sorghum (*Sorghum bicolor* L.), winter wheat (*Triticum aestivum* L.), and soybean [*Glycine max* (L.) Merr.]. A recent water survey of the Arkansas River Valley by the Colorado Department of Public Health and Environment (Austin, 1997) showed that $\text{NO}_3\text{-N}$ levels were high (>10 mg L^{-1}) in 14% of the wells tested in 1994, with most (47%) of the high-testing wells in Otero County, a major vegetable-producing area. Onion is produced in this area with high N fertilizer rates (100–300 kg N ha^{-1}) applied by growers to optimize yields without regard for soil test $\text{NO}_3\text{-N}$ levels (Bartolo et al., 1995, 1997). Ells et al. (1993) reported no response of onion to N fertilization in southeastern Colorado and found that N was lost from the root zone with furrow irrigation.

Soil test results from the lower Arkansas Valley area and Otero County indicate high levels of residual soil $\text{NO}_3\text{-N}$ (L. Sutherland, personal communication, 1998). In addition, salinity of the irrigation water delivered from the Arkansas River is relatively high, thus requiring frequent irrigation to minimize salt damage to emerging onion seedlings (Miyamoto, 1989) and ensure good stand establishment in this low-rainfall, high-evapotranspiration area. The $\text{NO}_3\text{-N}$ content of the irrigation water varies over the season, ranging from 1 to 4 mg L^{-1} in recent years. Most soils in the area are generally well drained but have shallow water tables (often within 4 m of the soil surface). Because of these factors, there is potential for $\text{NO}_3\text{-N}$ contamination of ground water in this area.

Shock et al. (2000) examined the use of sugarbeet to recover residual fertilizer N remaining in the soil profile following onion. They found that optimum sucrose production was possible without N fertilization following onion when sufficient residual N was present in the soil profile. Sugarbeet recovered a significant portion of the fertilizer N that was not used by the previous onion crop. Hills et al. (1983) also reported that sugarbeet recovered more residual soil profile N than corn. Pelter et al. (1992) recommended growing deep-rooted crops such as wheat (*Triticum aestivum* L.) or corn following

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Abbreviations: DM, dry matter; Ndff, nitrogen derived from fertilizer; –NF, no nitrogen fertilizer applied; +NF, nitrogen fertilizer applied; NFUE, nitrogen fertilizer use efficiency; NUE, nitrogen use efficiency.

onion to recover residual fertilizer N from the onion crop.

Little information is available on NFUE of onion (Sammis, 1997; Brown et al., 1988b), especially using ^{15}N -labeled fertilizer to determine NFUE. Onion is shallow rooted (generally <50 cm deep); therefore, NFUE is expected to be low in furrow-irrigated fields. The objectives of this study were to determine onion NFUE of N fertilizer applied during onion establishment and vegetative growth stages using ^{15}N -labeled fertilizer and to determine the recovery of residual fertilizer N by corn following onion in rotation.

MATERIALS AND METHODS

This study was conducted on a Rocky Ford silty clay soil (fine-silty, mixed, calcareous, mesic Ustic Torriorthents) at the Arkansas Valley Research Center, near Rocky Ford, CO. Two N fertilizer rates (0 and 224 kg N ha⁻¹) were established in 1998. Nitrogen source studies with onion in Idaho showed similar responses from different N fertilizer sources (Larkin and Thornton, 1995). Therefore, the KNO₃ fertilizer used in this study was expected to result in a similar response to N as urea [(NH₂)₂CO], which is often used by onion growers in the study area.

A randomized complete block design with four replications was used. Each N plot was four rows wide, with two onion rows (46 cm apart) per bed. The outside rows of each plot were located on half of the adjacent onion bed, with the two center rows of each plot located on the same bed. Furrow to furrow distance was 112 cm. The center two rows of each plot were used for plant sampling.

The 224 kg N ha⁻¹ treatment was applied in split applications of 112 kg N ha⁻¹ on 18 May 1998 and 25 June 1998. For the ^{15}N -labeled plots, the 112 kg N ha⁻¹ KNO₃ fertilizer labeled with ^{15}N was applied only once for each application date to the center two onion rows. Unlabeled KNO₃ fertilizer was applied at the alternate application date to bring the total split application to 224 kg N ha⁻¹. Unlabeled KNO₃ was applied to the two outside rows of the ^{15}N -labeled plots. All of the N fertilizer was band-applied as a liquid solution at a depth of 5 cm on the edge of the raised bed, approximately midway between the bottom of the irrigation furrow and the top of the bed using the "Follett et al. method" (Follett, 2001). Unlabeled N fertilizer was similarly applied to the two outside-border rows of onion in each plot receiving N fertilizer. Plot length for the ^{15}N -labeled plots was 244 cm for the 18 May application date and 183 cm for the 25 June application date. In addition, nonlabeled N fertilizer plots (224 kg N ha⁻¹) with split applications of N were included for biweekly plant sampling and final yield determination. The no fertilizer N (-NF) and nonlabeled fertilizer N (+NF) plots were each 305 cm long. Plot length varied among treatments because of the number of plant sampling times for each treatment.

Onion (variety X202, a sweet Spanish type) was seeded on 25 Mar. 1998 on raised beds with in-row onion spacing of about 7 to 8 cm and a plant population of about 235 000 plant ha⁻¹. A uniform stand of onion was established in the plot area. Onion was furrow-irrigated 10 times during the growing season. During the 4, 8, 13, and 24 April irrigations, only enough water was applied to wet the onion row to insure good onion establishment in this low-rainfall, high-evapotranspiration production area. Subsequent irrigations on 19 May, 3 and 25 June, 5 and 14 July, and 20 August 1998 had approximately 5 cm of water applied at each irrigation. Assuming a water application efficiency of 40 to 70% for furrow irrigation with

siphon tube (Martin et al., 1991), 2 to 3.5 cm of water was probably retained in the field with each irrigation. Irrigation runs were <120 m. Based on the experiences of the authors, the onion plots were irrigated only when water was needed to avoid stress on the onion plants, and water application was considered conservative compared with local grower practices. The NO₃-N concentration in the irrigation water ranged from 1.7 to 2.6 mg L⁻¹. Based on NO₃-N analyses of the irrigation water applied, <10 kg N ha⁻¹ was available in the irrigation water during the onion-growing season.

Onion samples (four adjacent plants from each of the two center rows per plot) were collected at 2-wk intervals from the -NF and +NF plots for cumulative growth and N uptake determination from 18 May until harvest (15 Sept. 1998). At harvest, two rows, approximately 1 m long, were harvested from each -NF and +NF plot. In the 18 May ^{15}N -labeled plots, plant samples (four adjacent plants from each of the two center rows per plot) were collected on 24 June, 8 July, and 15 September. In the 25 June ^{15}N -labeled plots, plant samples were similarly collected on 21 July and 15 September. At each sampling, onion was separated into tops and bulbs for dry matter (DM) and N uptake determination. The onion parts were weighed to determine fresh weight and then dried at 60°C to determine DM and water content.

Soil samples from the center of the onion bed of each plot were collected from the 0- to 180-cm profile at planting (23 Mar. 1998) and after onion harvest (17 Sept. 1998) in 30-cm increments for determination of NO₃-N content. Soil samples from the bed center of each plot were also collected on 18 May in 30-cm increments to a 60-cm depth for determination of NO₃-N content. After onion harvest, soil samples were collected at 15- or 30-cm depth increments from the center of the irrigation furrow, fertilizer band, 15 cm from onion row toward center of bed, and bed center of all plots for ^{15}N analysis.

Soil NO₃-N was determined by Cd reduction with an auto-analyzer (Lachat Instruments, 1989) on a 5:1 extract/soil ratio using 1 M KCl extracting solution. Soil test results from the plot area indicated soil pH ranged from 7.6 to 7.8, soil electrical conductivity from 0.1 to 0.2 S m⁻¹, and soil organic matter was 15 g kg⁻¹. Depth to water table at the Arkansas Valley Research Center ranges from 4.5 to 6 m. In November 1997, 49 kg P ha⁻¹ was applied to the plot area as monoammonium phosphate (11-52-0) fertilizer and incorporated by plowing. Before onion in 1998, the plot area was fallowed most of the summer of 1997, Zinnias (*Zinnia elegans* Jacq.) was produced in 1996, and carrot (*Daucus carota* L.) was produced in 1995.

The dry plant and soil samples collected for ^{15}N analysis were ground to pass a 150-μm screen and analyzed using a Carlo Erba C/N analyzer (Haake Buchler Instruments, Saddle Brook, NJ)¹ for total N concentration. The Carlo Erba was interfaced to a VG micromass 903 isotope-ratio mass spectrometer (VG Isogas, Cheshire, England) for determination of ^{15}N concentration in the soil and plant samples. Samples from the nonlabeled fertilizer plots were also analyzed for ^{15}N to obtain the natural abundance level of ^{15}N in the system. Soil N derived from fertilizer (Ndff) based on ^{15}N analysis is expressed as a percentage of the total soil N at the specified depth.

Nitrogen use efficiency of the onion crop was estimated by dividing the total N uptake of onion by the amount of N available to the crop (soil NO₃-N in 0-60 cm depth plus fertilizer N applied). This fraction was multiplied by 100 to obtain

¹ Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA-ARS.

Table 1. Soil profile $\text{NO}_3\text{-N}$ distribution near onion bed center before N fertilization and after onion harvest (September 1998), before corn planting (April 1999), and after corn harvest (November 1999).

Soil depth	23 Mar. 1998	17 Sept. 1998		21 Apr. 1999		9 Nov. 1999	
	-NF†	-NF	+NF‡	-NF	+NF	-NF	+NF
cm	Soil $\text{NO}_3\text{-N}$, kg ha^{-1}						
0-30	120	100	275	72	245	14	33
30-60	235	45	113	31	93	55	168
60-90	191	51	90	30	72	149	139
90-120	113	64	114	43	90	168	146
120-150	78	93	162	75	94	158	105
150-180	47	132	124	91	80	84	60
Total	785	485	879	342	674	627	651

† No N fertilizer applied to onion in 1998.

‡ Nitrogen fertilizer (224 kg N ha^{-1}) applied to onion in 1998.

percent NUE. The N added through the irrigation water was not included in the calculation because of the small quantity present in the irrigation water and the uncertainty of how much was actually retained in the soil.

Corn (hybrid DK642 IMI) was planted 10 May 1999 on the 1998 onion N plots with a 76-cm row spacing and no additional N fertilizer applied. Seeding rate was $76\,800 \text{ seeds ha}^{-1}$. The 1998 onion plot area was disked at a shallow depth ($<7.5 \text{ cm}$) and harrowed once before ridding and corn planting. Soil samples were collected from each plot within the area occupied by the center two rows of onion in 1998 on 1 April and 9 November 1999 for $\text{NO}_3\text{-N}$ and ^{15}N analysis. The corn plots were irrigated using siphon tubes on 22 June, 9 July, 20 August, and 22 September 1999 with approximately 10 cm of total water application to the plot area with each irrigation. Water was applied to every second irrigation furrow in an attempt to improve NUE of corn (Lehrsch et al., 2001). Assuming a water application efficiency of 40 to 70%, 4 to 7 cm of the applied water was retained in the plot area with each irrigation. The $\text{NO}_3\text{-N}$ concentration of the irrigation water ranged from 1.9 to 2.8 mg L^{-1} . The total amount of $\text{NO}_3\text{-N}$ available in the irrigation water during the corn growing season was $<9 \text{ kg N ha}^{-1}$. Corn plant samples were collected from a minimum 1-m^2 area of each N treatment on 25 Aug. 1999 for total biomass yield, N uptake determination, and ^{15}N analysis. Corn grain yields were estimated on 5 Oct. 1999 by harvesting the ears from a 2.5-m^2 or larger area of each plot. Average yield per N treatment was determined, including grain ^{15}N content.

Precipitation during the 1998 onion-growing period (25 March to 17 September) totaled 221 mm. During the noncrop period from October 1998 through March 1999, an additional 125 mm of precipitation was received. Above-average rainfall (466 mm) fell during the 1999 corn-growing season (April through October). The annual precipitation was 371 mm for 1998 and 507 mm for 1999. The 100-yr average annual precipitation for the site is 301 mm. Both growing seasons had above-average precipitation.

Analysis-of-variance procedures were conducted using SAS statistical procedures (SAS Inst., 1991). All differences discussed are significant at the $P \leq 0.05$ probability level unless otherwise stated. An LSD was calculated only when the analysis-of-variance F -test was significant at the $P \leq 0.05$ probability level.

RESULTS AND DISCUSSION

Initial soil $\text{NO}_3\text{-N}$ levels available to the onion crop on 23 Mar. 1998 averaged $355 \text{ kg ha}^{-1} \text{ NO}_3\text{-N}$ in the 0- to 60-cm profile (Table 1). In the 0- to 180-cm soil depth, $785 \text{ kg ha}^{-1} \text{ NO}_3\text{-N}$ was present. Soil $\text{NO}_3\text{-N}$ levels in the 0- to 60-cm depth on 18 May before N fertilizer application averaged $407 \text{ kg ha}^{-1} \text{ NO}_3\text{-N}$ near the center

of the onion bed. This would indicate a slight increase in soil $\text{NO}_3\text{-N}$ in the onion bed from 23 March to 18 May. This increase in soil $\text{NO}_3\text{-N}$ may indicate $\text{NO}_3\text{-N}$ release from mineralization of soil organic matter, movement of soil $\text{NO}_3\text{-N}$ toward the center of the onion bed with the irrigation water, or both. Brown et al. (1988a, 1988b) reported an increase in soil $\text{NO}_3\text{-N}$ in the center of onion beds in Idaho as the growing season progressed with furrow irrigation. These initial levels of soil $\text{NO}_3\text{-N}$ are typical of the Arkansas Valley onion production area. Nitrogen application to onion would not be recommended at these soil $\text{NO}_3\text{-N}$ levels (Schwartz and Bartolo, 1995). However, western onion growers and onion growers in this production area often apply N to the onion crop regardless of soil test $\text{NO}_3\text{-N}$ level to ensure a large-size marketable onion (Drost, 1999; M.E. Bartolo, personal communication).

Onion Yield

Dry matter accumulation by tops and bulbs was slow during the early part of the growing season, with a more rapid increase in both bulbs and tops as bulbing began in July (Fig. 1). Dry matter accumulation in the tops increased until mid- to late July and then leveled off through August and declined in September. There was no significant difference in top DM accumulation between the -NF and +NF treatments. The DM accumulation in the onion bulbs increased as the growing season progressed until harvest on 15 Sept. 1998 (Fig. 1). Dry

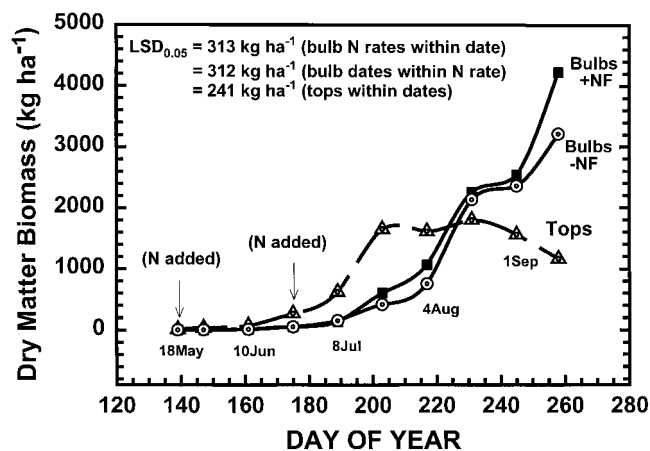


Fig. 1. Biomass production of tops as a function of day of year and bulbs as a function of day of year and N rate (+NF, N fertilizer applied; -NF, no N fertilizer applied).

matter accumulation in the bulbs tended to be greater with the application of 224 kg N ha⁻¹ than without N fertilization, with the difference being significant only at the final harvest on 15 September.

Fresh bulb yield increased rather slowly from emergence until about mid-July (day of year 200) for both N treatments and then increased rapidly until harvest (Fig. 2). From August through September, fresh bulb weight tended to be greater with N applications than without N, with the difference being significant only at the final harvest (15 September). Fresh bulb yields obtained in this study were similar to the average yield (42.6 Mg ha⁻¹) reported for Colorado in 1998 by Colorado Agricultural Statistics Service (2000). At the 15 September harvest, the additional 11.6 Mg ha⁻¹ bulb fresh weight with the application of 224 kg N ha⁻¹ above that of the -NF treatment was not expected because of the high level of initial soil NO₃-N. Based on this 1-yr result, the authors would not recommend this level of N fertilization with the high level of soil NO₃-N present at onion seeding. Other studies have shown that no response to N fertilization would be expected with the high level of soil NO₃-N present at seeding in this study (Ells et al., 1993). Assuming that the entire increased fresh weight with N application was marketable onion, the estimated value of the increased onion yield with N application in 1998 was about \$3325 ha⁻¹ based on a 5-yr average value of onion in Colorado (Colorado Agricultural Statistics Service, 2000). This potential gross return compared with the cost of N may indicate why western onion growers often add fertilizer N even with high soil NO₃-N levels. Even if only 70% of the increased yield was marketable onion and the price was slightly less, the gross return compared with cost of N input would still be large. This type of N management, however, ignores the impact of excess N on ground water quality.

Nitrogen Uptake by Onion

The concentration of N in the onion tops and bulbs generally declined as the growing season progressed

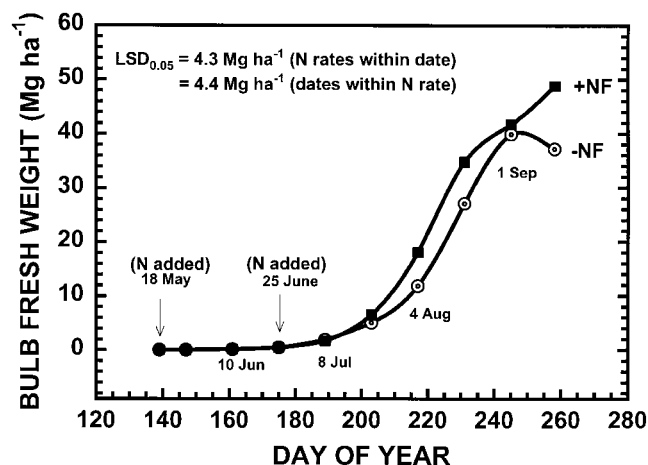


Fig. 2. Bulb fresh weight production as a function of sampling date and N fertilizer rate (+NF, N fertilizer applied; -NF, no N fertilizer applied).

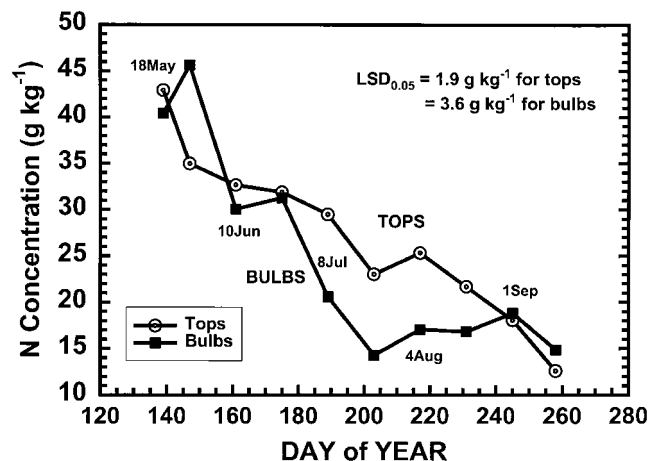


Fig. 3. Nitrogen concentration in onion tops and bulbs as a function of sampling date.

(Fig. 3). Bulb N concentration hit a low in mid-July and then increased slightly during the August and early September sampling dates before declining to the lowest concentration at final harvest. Nitrogen concentration in tops and bulbs did not vary significantly with N fertilization treatment throughout the growing season.

Nitrogen uptake by tops plus bulbs increased as the growing season progressed, with N uptake being greater with N fertilization than without N fertilization from mid-July until final harvest (Fig. 4). Total top-plus-bulb N uptake at final harvest was 80 and 60.5 kg N ha⁻¹ with +NF and -NF, respectively. Nitrogen uptake by the bulbs increased throughout the growing season, with greater bulb N uptake with +NF from early August through harvest compared with -NF. Total N uptake in the bulb at final harvest was 66 and 45.4 kg N ha⁻¹ with +NF and -NF, respectively.

Based on the N uptake pattern by onion (Fig. 4), the N need of onion early in the season was very low. Thus, delaying N application until just before bulbing (late June) appears to be a sound management decision and could improve NFUE. Application of N during the rapid accumulation of bulb DM coincides with the period of maximum N need by onion and would possibly reduce

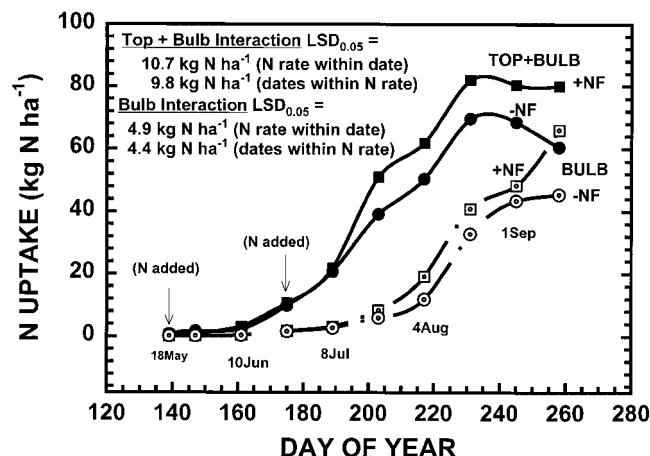


Fig. 4. Nitrogen uptake in tops plus bulbs and in bulbs as a function of sampling date and N fertilization (+NF, N fertilizer applied; -NF, no N fertilizer applied). Significant N rate \times date interactions are shown.

$\text{NO}_3\text{-N}$ leaching potential. Pelter et al. (1992) reported a similar level of N removal per unit of fresh bulb weight (1.6 kg N Mg^{-1}) as we found in this study (1.4 kg N Mg^{-1}). They recommended that all N applications be completed by late June in the Pacific Northwest to ensure proper bulb maturation and reduce storage losses. In contrast, results from our study with high levels of soil $\text{NO}_3\text{-N}$ at seeding suggest that N application be delayed until late June to improve NFUE and still maintain high yields. A single, lower-rate application of N would probably be sufficient in this high soil $\text{NO}_3\text{-N}$ environment.

Based on the ^{15}N analysis of onion plants harvested on 24 June (37 d after 18 May ^{15}N application), the Ndff in the tops and bulbs was 30 and 28%, respectively. On 8 July (51 d after ^{15}N application), the Ndff in the tops and bulbs was 17 and 16%, respectively. The decline in Ndff is likely due to the increased availability of residual soil $\text{NO}_3\text{-N}$ as the onion root system expanded. At final harvest on 15 September (120 d after ^{15}N application), the Ndff in the tops and bulbs was 13 and 15%, respectively.

Based on the ^{15}N analysis of onion plants harvested on 21 July (27 d after the 25 June ^{15}N application), the Ndff in the tops and bulbs was 26 and 25%, respectively. At final harvest on 15 September (82 d after ^{15}N application), the Ndff in the tops and bulbs was 25 and 26%, respectively. The final-harvest Ndff data show that the N fertilizer applied on 25 June was more effective in satisfying the onion plant N needs than the 18 May N application.

Based on the total top-plus-bulb N uptake, NFUE was 11% for the 18 May application and 19% for the 25 June application date. The onion NFUE of the 224 kg N ha^{-1} applied for the season was about 15%. Thus, 85% of the fertilizer N remained in the soil profile or was otherwise unaccounted for after the onion harvest. These NFUE values are slightly lower than those reported by Brown et al. (1988b) in Idaho of 19 to 26% for high N rates, depending on method of N application.

Nitrogen use efficiency of onion, based on soil $\text{NO}_3\text{-N}$ (0–60 cm depth) plus fertilizer N applied (total of 579 kg N ha^{-1}), was very low in this study. Total N uptake in tops plus bulbs, based on DM accumulation and plant N concentration, was only 80 kg N ha^{-1} , with a NUE of 13.8% or $9.2 \text{ kg DM ha}^{-1} \text{ kg}^{-1}$ available N for the 224 kg N ha^{-1} fertilizer treatment. With no N fertilizer applied, NUE was 17% or $12.5 \text{ kg DM ha}^{-1} \text{ kg}^{-1}$ available N.

Nitrogen use efficiency based on bulb N removal or harvested portion of the crop was $7.3 \text{ kg DM ha}^{-1} \text{ kg}^{-1}$ available N for the 224 kg N ha^{-1} fertilizer treatment. Total NUE was 11.4% for N removed in bulbs. With no fertilizer N applied, NUE was 12.8% for N removed in bulbs. Nitrogen use efficiency is low in this study because of the high level of available N in the root zone at planting compared with the total amount of N taken up by the onion plants.

Plant samples were collected from inside and outside of the ^{15}N microplot area to detect potential lateral movement of ^{15}N fertilizer and to compute relative frac-

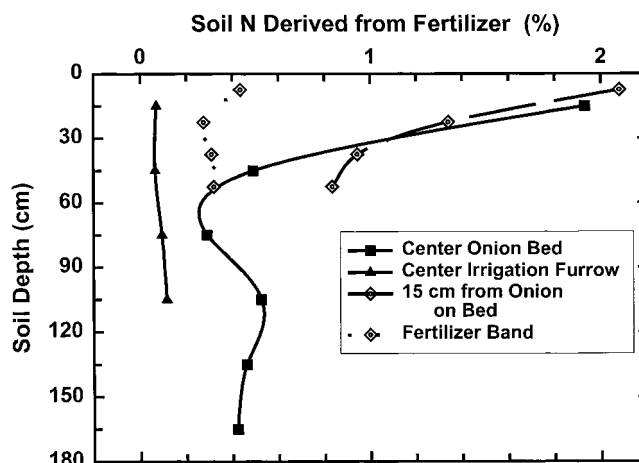


Fig. 5. Distribution of residual ^{15}N fertilizer in soil after onion harvest on 17 Sept. 1998 as a function of soil depth and soil sample location.

tion of plant ^{15}N inside and outside of the microplots. Results of these measurements (Follett, 2001) show essentially no lateral movement of ^{15}N across the irrigation furrow between onion beds. Average maximum detectable distance that the ^{15}N had moved along the rows, beyond the microplot ends, as a result of cultural practices and irrigation was 0.4 and 0.3 m for the 18 May and 25 June applications of ^{15}N fertilizer, respectively.

Soil samples collected after onion harvest from the ^{15}N -labeled plots show that the N fertilizer applied had moved through the soil profile with irrigation water. The highest concentration of Ndff in the soil was located in the upper 30 cm near the center of the onion bed (Fig. 5, average of both N application dates). The amount of Ndff was very low in the soil samples collected from the center of the irrigation furrow. The amount of Ndff remaining in the 0- to 60-cm soil profile in the fertilizer band area was slightly higher than in the irrigation furrow but much lower than that found in the onion bed 15 cm in from the onion row (toward bed center) and in the bed center. These data show that the labeled fertilizer had moved from the fertilizer band toward the bed center with the irrigation water, with the highest ^{15}N levels found near the soil surface and levels decreasing with soil profile depth. This is consistent with the soil $\text{NO}_3\text{-N}$ movement toward bed center observed by Brown et al. (1988b) in Idaho. Labeled ^{15}N fertilizer in our study was also found at the 150- to 180-cm soil depth of soil cores taken from the bed center, thus indicating deep leaching of N fertilizer and N loss from the root zone of onion.

The movement of fertilizer ^{15}N and residual soil $\text{NO}_3\text{-N}$ toward the bed center may explain why an increase in onion fresh bulb yield was observed in this study with N application. Because the furrow irrigation water had moved the soil $\text{NO}_3\text{-N}$ and fertilizer N from the onion root zone toward the bed center, the onion plants may have become slightly N deficient toward the end of the growing season in the -NF plots. Thus, the N fertilizer added in late June may have sufficiently enhanced N nutrition of the onion to result in the increased bulb yield. Changing irrigation methods from

Table 2. Soil distribution of fertilizer N following onion and corn harvest from N derived from ^{15}N -labeled fertilizer applied to onion in 1998 (sampling location near center of onion bed).

Soil depth cm	After onion harvest (17 Sept. 1998)		After corn harvest (9 Nov. 1999)	
	N applied 18 May 1998	N applied 25 June 1998	N applied 18 May 1998	N applied 25 June 1998
	Ndff†, %			
0–30	1.86	2.00	0.31	0.24
30–60	0.36	0.62	1.30	0.88
60–90	0.19	0.40	0.43	0.49
90–120	0.57	0.48	0.36	0.35
120–150	0.32	0.60	0.13	0.21
150–180	0.17	0.67	0.07	0.42
Avg.	0.58	0.79	0.43	0.43

† Ndff, N derived from fertilizer as a percent of the total soil N.

furrow to sprinkler or drip irrigation would probably enhance NUE by onion.

Residual soil $\text{NO}_3\text{-N}$ levels following onion harvest remained high in the 0- to 60-cm profile and in the 0- to 180-cm profile (Table 1). The $-\text{NF}$ plots had soil $\text{NO}_3\text{-N}$ levels that were 300 kg ha^{-1} $\text{NO}_3\text{-N}$ less in the 0- to 180-cm profile in September 1998 than was present in March 1998. The $+\text{NF}$ plots had gained about 100 kg ha^{-1} $\text{NO}_3\text{-N}$ from March to September 1998. The greater amount of $\text{NO}_3\text{-N}$ in the 120- to 180-cm soil depth in September 1998 after onion harvest compared with March 1998 indicates that $\text{NO}_3\text{-N}$ from the shallower soil depths had moved to the deeper soil depths in the profile during the growing season, which is supported by the soil ^{15}N data in Table 2 and Fig. 5. Sufficient residual soil $\text{NO}_3\text{-N}$ was present after onion harvest to produce a high-yielding corn crop the following year without further N fertilization. The spatial variability of the residual soil $\text{NO}_3\text{-N}$ may be high under the onion bed, as documented by the distribution of fertilizer ^{15}N in the onion bed (Fig. 5).

Corn Yields and Nitrogen Uptake

Total corn biomass yields determined on 25 Aug. 1999 from the same N plots used in 1998 for onion, without further N fertilizer application, were not significantly different between the $-\text{NF}$ and $+\text{NF}$ treatments, with DM yields of 17.3 and 17.7 Mg ha^{-1} , respectively. Total biomass N uptake on 25 August was 196 and 213 kg N ha^{-1} for the $-\text{NF}$ and $+\text{NF}$ treatments, respectively, which were significantly different at $P = 0.069$. The amount of the total biomass N uptake derived from N fertilizer in the $+\text{NF}$ plots was 26.6 and $27.5 \text{ kg N ha}^{-1}$ for the 18 May 1998 and 25 June 1998 ^{15}N application dates, respectively, which were not significantly different. Assuming that total N uptake by corn was near maximum at the 25 Aug. 1999 biomass sampling date, an additional 24% of the 224 kg N ha^{-1} applied to onion in 1998 was recovered by the 1999 corn crop.

The 1999 corn grain yields on 10 Oct. 1999 following the 1998 onion crop were not significantly different between the $-\text{NF}$ and $+\text{NF}$ treatments, with yields (155 g kg^{-1} moisture content) of 15.0 and 14.7 Mg ha^{-1} , respectively. Total grain N uptake was not significantly different between the two N treatments, with N uptake levels of 158.3 and $158.5 \text{ kg N ha}^{-1}$ for the $-\text{NF}$ and $+\text{NF}$ treatments, respectively. Based on ^{15}N analysis,

the amount of N fertilizer recovered in the $+\text{NF}$ plots by corn grain in 1999 was 18.8 and $15.0 \text{ kg N ha}^{-1}$ for the 18 May and 25 June 1998 ^{15}N applications, respectively, which were significantly different at $P = 0.098$. Of the 224 kg N ha^{-1} applied to the onion crop in 1998, about 15% of the N was removed in the corn grain in 1999. With the high levels of available soil $\text{NO}_3\text{-N}$ at planting (Table 1), and addition of a small amount of $\text{NO}_3\text{-N}$ with the irrigation water, the low recovery of the N fertilizer by the onion (15%) and corn (24%) crops was probably to be expected. Approximately 39% of the N fertilizer applied in 1998 was taken up by the two crops in this high residual soil N environment. The ^{15}N analysis on soil samples collected after corn harvest shows that the highest concentration of N fertilizer was still in the 0- to 60-cm depth (Table 2). The average concentration of Ndff in the soil profile (0–180 cm depth) in November 1999 was about 25 to 50% less than that found following onion harvest in September 1998.

Residual soil $\text{NO}_3\text{-N}$ remained high in the 0- to 180-cm profile following corn harvest (Table 1). The soil $\text{NO}_3\text{-N}$ levels were similar between the $-\text{NF}$ and $+\text{NF}$ treatments after corn harvest in 1999. The reason for the large increase in $\text{NO}_3\text{-N}$ level in the $-\text{NF}$ plots and not the $+\text{NF}$ plots from April to November 1999 is not understood. Although soil-sampling location was at the center of the onion bed in 1998, land preparations (re-ridging) for the 1999 corn crop resulted in less exact sampling locations in 1999. This, along with the spatial variability (Fig. 5) that was encountered, may have caused the high and variable soil $\text{NO}_3\text{-N}$ levels observed, especially for the fall 1999 soil sampling. More important is the data in Table 2, which shows that fertilizer N (using ^{15}N tracer) had moved downward in the soil profile to a depth of at least 180 cm by the fall of 1998 and remained at that depth through the fall of 1999. Nitrogen mineralization probably contributed some of the increased soil $\text{NO}_3\text{-N}$. Irrigation water had $<9 \text{ kg N ha}^{-1}$ available during the corn growing season. A rise in the shallow ground-water table during the corn irrigation season could have moved soil $\text{NO}_3\text{-N}$ positioned above the water table upward into the root zone. Martin et al. (1991) point out that $\text{NO}_3\text{-N}$ can move upward into the root zone from shallow water tables. At the November 1999 soil sampling, the soil in the 150- to 180-cm depth was near saturation because free water was visible in the soil sample. Depth to the water table was appar-

ently very shallow. Therefore, upward movement of $\text{NO}_3\text{-N}$ from deeper soil depths may explain some of the high and variable soil $\text{NO}_3\text{-N}$ levels observed after the 1999 corn harvest. Sufficient soil $\text{NO}_3\text{-N}$ remained after corn harvest to produce another high-yielding corn crop with minimal or no N fertilizer needed to optimize grain yields.

SUMMARY AND CONCLUSIONS

Nitrogen fertilization of onion may be contributing to the high levels of $\text{NO}_3\text{-N}$ in the soils and ground water in the Arkansas River Valley of southeastern Colorado. Fertilizer ^{15}N applied to onion on 18 May and 25 June 1998 was detected at 180-cm soil depth in September 1998. Fertilizer N use efficiency by onion was low, averaging only 15% in this study. The results of this study, using ^{15}N -labeled fertilizer to estimate NFUE, supports the low NFUE observed for onion in other studies (Sammis, 1997; Brown et al., 1988b). Because N uptake by onion is minimal early in the growing season, delaying N fertilizer application until late June and reducing N rates may improve NFUE of onion in Colorado when soil $\text{NO}_3\text{-N}$ levels are high at seeding.

Recovery by corn in 1999 of fertilizer N applied to onion in 1998 was also low, only 24%. Total recovery of the fertilizer N by the two crops was 39%. Consequently, if an alternative deep-rooted crop that more effectively scavenges residual fertilizer N can be grown following onion in rotation, it needs to be considered in place of corn to reduce the risk of $\text{NO}_3\text{-N}$ contamination of ground water. An estimated 158 kg N ha^{-1} was removed in the corn grain while 213 kg N ha^{-1} was removed in the total corn biomass. Therefore, removal of the corn as silage would remove more N from the system than removal as grain.

Fertilizer N applied on the edge of the irrigation furrow near the onion row was moved toward the center of the onion bed with the irrigation water. Planting corn on the onion beds in close proximity to the $\text{NO}_3\text{-N}$ concentration may have improved fertilizer N recovery by the corn crop in this study. This would have required narrow corn row spacing but would have positioned the corn roots near the soil zone with the highest levels of residual fertilizer N. The results from this study indicate that some of the N fertilizer applied to the onion was leached out of both the onion and corn root zones. Onion growers in southeastern Colorado need to delay N fertilizer application until near onion bulbing and base N fertilization rates on available soil $\text{NO}_3\text{-N}$ in the onion root zone to improve NFUE and reduce the potential negative impacts of $\text{NO}_3\text{-N}$ on ground water quality. Soil testing before N fertilizer application to crops in the Arkansas River Valley is recommended to improve NUE and reduce the quantity of $\text{NO}_3\text{-N}$ available for leaching. Slow-release N fertilizers (Brown et al., 1988a, 1988b) and growing cover crops between major crops should be considered to reduce $\text{NO}_3\text{-N}$ leaching potential. Changing to more efficient irrigation methods, such as sprinkler or drip, should improve water

management, reduce $\text{NO}_3\text{-N}$ leaching potential, and improve NUE.

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